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Original Research Report

Age-Related Differences in Plausibility-Checking Strategies During Arithmetic Problem Verification Tasks

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Abstract

Objectives: We examined whether older adults use plausibility-checking strategies while verifying arithmetic problems. We also tested trial-to-trial modulations of plausibility-checking strategies, and aging effects on these sequential modulations.
Method: We asked young and older adults to verify arithmetic problems that violated or respected arithmetic rules (i.e., $5 \times 16 = 87$. True/False?).
Results: Both young and older adults solved problems violating parity rule and five rule more quickly than problems violating no rule. We also found that both age groups had better performance when both five rule and parity rule are violated than when only one or no rules are violated. These results suggest age invariance in using rule-violation checking strategies and a smaller, but still efficient, strategy combination in older adults. Finally, for young adults only, strategy combination was larger following problems violating rules than after problems respecting rules.
Discussion: These findings have important implications regarding mechanisms underlying age-related differences in using rule-violation checking strategies to verify arithmetic problems and in combining two strategies into a single, more efficient one.

Keywords: Aging—Arithmetic—Sequential modulations of strategies—Strategies—Strategy combination

Three decades of empirical and theoretical research have shown that people know and use multiple strategies to accomplish a wide variety of cognitive tasks (see Siegler, 2007, for a review). A strategy can be defined as “a procedure or a set of procedures for achieving a higher level goal or task” (Lemaire & Reder, 1999, p. 365). Research also showed age-related changes in strategic variations. Older adults use fewer strategies than young adults, use available strategies with different proportions, execute strategies less efficiently, and select the best strategy on each problem less often (see Lemaire, 2010, for an overview).

In arithmetic, multiple strategy use has been found in both young and older adults, although age-related differences in strategic variations have also been reported (see Duverne & Lemaire, 2005, for an overview). These age-related differences in arithmetic have been well-documented in production tasks, in which participants are given a problem (e.g., $8 \times 7 =?$) and have to find the answer. Research in production tasks showed that older adults use retrieval strategy (i.e., direct access to the correct solution in memory) more frequently than young adults (e.g., Thevenot, Castel, Danjon, Fanget, & Fayol, 2013), although this strategy is executed less efficiently by older adults than by young adults (e.g., Geary & Wiley, 1991; Geary, Frensch, & Wiley, 1993). Age-related differences in strategies have been much less documented in arithmetic problem verification tasks, one of the most often used tasks in research on arithmetic. In arithmetic problem verification tasks, participants are given an arithmetic equation and have to say whether this equation is true or false (e.g., $8 \times 7 = 41$. True? False?). This task has often been used because it is easily accomplished by participants of all ages and cognitive conditions, it yields performance (i.e., reaction times, percentages of errors) that are easily analyzed, reliable, and are valid measures of underlying cognitive processes.

Previous research has shown that participants can use several strategies to verify arithmetic problems (Allen, Ashcraft, & Weber, 1992; Allen, Smith, Jerge, & Vires-Collins, 1997; Allen et al., 2005; Duverne & Lemaire, 2005; Duverne, Lemaire, & Vandierendonck, 2008; El Yagoubi, Lemaire, & Besson, 2005). They can, as in production tasks, calculate the correct answer, or retrieve the solution directly from long-term memory. They also can use a variety of plausibility-checking strategies. Plausibility-checking strategies are used when participants do not calculate or retrieve the exact answer, but quickly estimate that the proposed answer cannot be true.

Several plausibility-checking strategies have been documented in the arithmetic literature. For example, participants use a fast, plausibility-checking strategy when they reject a large-split problems like $8 \times 4 = 39$ when the proposed answer is too far from the correct answer (Ashcraft & Battaglia, 1978; De Rammelaere, Stuyven, & Vandierendonck, 2001; Zbrodoff & Logan, 1990), a parity-rule violation checking strategy (Krueger & Hallford, 1984; Krueger, 1986; Lemaire & Fayol, 1995; Lemaire & Reder, 1999; Masse & Lemaire, 2001) when the equation violates the parity rule (i.e., when at least one of the two operands is even, the product is also even; otherwise the product is odd; e.g., $4 \times 13 = 51$), and a five-rule violation checking strategy (Lemaire & Reder, 1999; Siegler & Lemaire, 1997) when the answer violates the five rule (i.e., products of problems including five as an operand end with either five or zero; e.g., $5 \times 14 = 70$). Indeed, participants are faster and more accurate (a) when the five rule is violated (e.g., $14 \times 5 = 62$) than when it is respected (e.g., $5 \times 14 = 60$), and (b) when the parity rule is violated ($4 \times 38 = 149$) than when it is respected (e.g., $4 \times 38 = 154$). Previous findings also showed that young participants showed larger benefits while using the five-rule violation checking strategy compared with the parity-rule violation checking strategy. Moreover, recently, Hinault, Dufau, and Lemaire (2014) found that young adults have better performance when both five and parity rules are violated (e.g., $5 \times 17 = 86$) than when only five or parity rule is violated. The authors proposed that participants verified the two-rule violation problems by combining both rule verification strategies into a single, more efficient strategy. This strategy combination led people to check whether (a) an equation with five and an even operand had a product that ends with zero, and (b) an equation with five and an odd operand had a product that ends with five.

Although many studies have been conducted on how age influences strategic variations during adult development (see Lemaire, 2010, for an overview), none investigated whether young and older participants differ in rule-violation checking strategies. Thus, we ignore if older adults use rule-violation checking strategies like young adults when they solve arithmetic problems. In other cognitive tasks like sentence verification tasks, research has found that older adults can use plausibility-checking strategies (e.g., Reder, Wible, & Martin, 1986). However, in arithmetic, several studies revealed that older adults do not show much split effects or show smaller split effects than young adults (Allen et al., 1992, 1997, 2005; Duverne & Lemaire, 2005; Duverne et al., 2008; El Yagoubi et al., 2005) resulting from older adults using exact calculation strategy only, and not fast plausibility, split-checking strategy. This suggests that, in verification tasks, older adults could also prefer exact calculation strategy on both true and false problems than rule-violation checking strategies when appropriate. If older adults use rule-violation checking strategies, we do not know if, like young adults, they are faster while using the five-rule violation checking strategy than while using the parity-rule violation checking strategy, and if they are faster on two-rule violation problems than on one-rule violation problems.

Finally, previous research showed sequential modulations during strategy execution (Lemaire & Lecacheur, 2010; Luwel, Onghena, Torbeyns, Schillemans, & Verschaffel, 2009; Schillemans, Luwel, Onghena, & Verschaffel, 2011; Schillemans, Luwel, Ceulemans, Onghena, & Verschaffel, 2012; Uittenhove & Lemaire, 2012, 2013) as well as aging effects on sequential modulations (Ardiale and Lemaire, 2012; Lemaire & Leclère, 2014). For example, Lemaire and Leclère (2014) found that older adults tended to repeat the same strategy across two consecutive problems more often than young adults. Ardiale and Lemaire (2012) found larger strategy switch costs than young adults. However, we do not know whether young adults modulate the use of rule-violation checking strategies from one trial to the next, and if these sequential modulations change during aging. We tested these possibilities in the present study.

The first goal of the present study was to investigate aging effects on rule-violation checking strategies during arithmetic problem verification tasks. We tested age-related differences in performance on problems that violated only five rule (e.g., $5 \times 32 = 164$), only parity rule (e.g., $5 \times 12 = 65$), both parity and five rules (e.g., $5 \times 31 = 158$), or no rule ($5 \times 26 = 140$). We predicted to replicate previous findings that young participants are faster (a) on parity-rule and five-rule violation problems compared with no-rule violation problems, (b) on five-rule violation than on parity-rule violation problems, and (c) on two-rule violation problems than on one-rule violation problems. Moreover, following previous work using arithmetic problem verification tasks (e.g., Allen et al., 1992, 1997, 2005; Lemaire & Reder, 1999), we predicted to find better performance on five problems than on non-five problems, on false problems compared with true problems, as well as larger true–false differences for non-five than for five problems.

Most originally, we tested age-related differences in parity-rule violation, five-rule violation, and both-rule violation problems. Of specific and unique interest was whether older adults would use the fast five-rule violation checking strategy and the parity-rule violation checking strategy, as well as whether, like young adults, they are faster using the former than using the latter. We tested the prediction that older adults use such plausibility-checking strategies based on rule violation while verifying arithmetic problems. Alternatively, older adults may not use fast plausibility-checking strategies on rule-violation problems but only exact calculation. This is possible following previous research that showed (a) that older adults use fewer strategies than young adults in many cognitive tasks, arithmetic problem solving included (e.g., Duverne & Lemaire, 2004; El Yagoubi et al., 2005; Hodzik & Lemaire, 2011; Lemaire & Leclère, 2014), and (b) decreased, or lack of, split effects in older adults (Allen et al., 1992, 1997, 2005; Duverne & Lemaire, 2005; Duverne et al., 2008; El Yagoubi et al., 2005), suggesting that older may not use plausibility-checking strategies on large-split problems.

Also, we asked whether older adults combine parity-rule violation and five-rule violation checking strategies into a single strategy to verify two-rule violation problems, like Hinault and colleagues (2014) recently found in young adults. Alternatively, given aging effects on working memory (for a review see Park & Reuter-Lorenz, 2009), we could expect older adults to be impaired during activation of both parity-rule and five-rule and their combination into a single strategy. Indeed, with fewer resources, older adults may choose to rely more on only one rule-violation checking strategy and use the fastest of the parity-rule violation or the five-rule violation checking strategy. All in all, these outcomes were expected to document aging effects on using rule-violation checking strategies and on combining two strategies into a single, more efficient one.

The final original goal of this study was to test sequential modulations of rule-violation checking strategies. Such sequential modulations would be seen in benefits associated with rule-violation checking strategies on current problems being modulated by whether the immediately preceding problem violated or respected arithmetic rules. In particular, these benefits were expected to be larger following problems violating rules compared with problems respecting rules. This should occur if using the rule-violation checking strategy on a problem makes this strategy more readily available on the next problem. Previous research suggests potential age-related differences in such strategy sequential modulations (Ardiale and Lemaire, 2012; Lemaire & Leclère, 2014). Declining processing resources with age may lead older adults to approach each problem individually without being able to benefit from rule-violation repetition across successive problems. Age-related differences in sequential modulations of rule-violation checking strategies will occur if postexecution residual activation dissipates more quickly in older than in young adults. As this just executed strategy is no longer in a high state of activation, older adults would not be able to execute it more quickly than if it is still in a high state of activation while encoding the current problem. Alternatively, older adults could be as able as young adults to use rule-violation checking strategies on current problems after just using them on the immediately preceding problems. Indeed, several studies found cases of age equivalence in sequential modulations of strategy execution (Lemaire & Hinault, 2014; Uittenhove & Lemaire, 2013).

Method

Participants

Twenty-six young and 26 older adults participated in this experiment (see participants' characteristics in Table 1).

Stimuli

The stimuli were multiplication problems presented in a standard form ($a \times b = c$) with "a" as a single digit and "b" as a double digit, or reversed. Single-digit operands ranged from three to eight, whereas two-digit operands ranged from 12 to 98.

Each participant solved 640 problems. There were 320 five problems (e.g., $5 \times 89 = 445$) and 320 non-five problems (e.g., $3 \times 17 = 51$). Half the problems were true problems (e.g., $4 \times 26 = 104$) and half false problems (e.g., $5 \times 41 = 201$). Thus, there were 160 problems of each type (i.e., five true, five false, non-five true, and non-five false problems). Half the five problems had an even non-five operand (e.g., $5 \times 64 = 320$), whereas the other problems had an odd non-five operand (e.g., 5 x 93 = 465). Regarding false five problems, there were 40 of each type (i.e., no-rule

Table 1. Participants' Characteristics

Variable	Young adults	Older adults	*F*
N	26	26	—
Age in years and months (range)	21.03 (2.8)	74.7 (7.8)	—
Years of education (range)	15 (2.8)	13.3 (3.8)	0.40
MHVS	26 (3.4)	27.2 (4.1)	0.88
Arithmetic fluency	68 (18.7)	77.3 (22.1)	2.75
MMSE	—	29.2 (0.9)	—

Notes: MHVS = French version of the Mill–Hill Vocabulary scale (Deltour, 1993). MHVS consist of 33 items distributed across three pages. Each item was a target word followed by six proposed words, and the task consisted in identifying which of the proposed word had the same meaning that the target word. Arithmetic fluency = Score obtained in a paper-and-pencil arithmetic test (French Kit; French, Ekstrom, & Price, 1963) in which participants have to solve as many basic arithmetic problems (e.g., 53-18) as possible in 8 min; MMSE = Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975). None of the older adults obtained an MMSE score <27; therefore, none were excluded.

violation problems, five-rule violation problems, parity-rule violation problems, two-rule violation problems). Non-five problems included an equal number of two even operands, two odd operands, and one even operand (even × odd or odd × even).

Following previous works in arithmetic (e.g., Ashcraft & Battaglia, 1978), false problems were created by varying splits (i.e., differences) between correct and proposed products. Using different splits made it possible to create problems either consistent or inconsistent with five and parity rules. The parity rule states that when at least one of the two operands is even, the product is even; otherwise it is odd. The five-rule states that the product of an operand multiplied by five ends with either five or zero. For non-five problems, the false problems had products with splits of ± 1, ± 2, ± 3, ± 4, ± 7, ± 9, ± 14, or ± 20 between proposed products and correct products. This resulted in half of the non-five problems violating the parity rule (e.g., 6 × 17 = 103) and the other problems respecting the parity rule (e.g., 6 × 23 = 134). Four types of false five problems were tested: (a) parity-rule only violation problems, with splits of ± 5 or ± 15 from correct products (e.g., 5 × 12 = 65), (b) five-rule only violation problems, with splits of ± 2 or ± 4 from correct products (e.g., 5 × 32 = 162), (c) parity- and five-rule violation problems, with splits of ± 1 or ± 3 from correct products (e.g., 5 × 31 = 158), and (d) no-rule violation problems, with splits of ± 10 or ± 20 from correct products (e.g., 5 × 26 = 140).

Based on previous findings in arithmetic (see Geary, 1994 or Campbell, 2005, for reviews), we controlled the following factors: (a) no double-digit operand had zero or five as unit digit, (b) no double-digit operand had five as decade digit (e.g., 53), (c) no double-digit operand had the same unit digit as decade digit (e.g., 44), (d) the size and side of double-digit operands were controlled, (e) half the problems had the double digit in the left position (e.g., 26 × 5 = 140) and half in the right position (e.g., 5 × 26 = 140), (f) mean splits did not differ across five problems (mean = 7.5) and non-five problems (mean = 7.5), $t(159) < 1$. Moreover, half the proposed products were larger than the correct products and the other half smaller than the correct products, for both five and non-five problems, (g) the magnitude of the proposed products did not differ significantly between five problems (mean = 275) and non-five problems (mean = 275), $t(159) < 1$. Furthermore, the magnitude of the proposed products did not differ significantly between parity-rule violation problems (mean = 275), five-rule violation problems (mean = 275), no-rule violation problems (mean = 275), and two-rule violation problems (mean = 275), $F < 1$. Finally, no false problem had a proposed product equal to 100.

Procedure

Stimuli were presented on a 800 × 600 resolution computer screen in a 18-point Courier New font. Problems were displayed horizontally in the center of the screen in the form of "*a* x *b* = *c*." Participants were instructed to press the "F" key on an AZERTY keyboard if the problem is true and the "J" key if it is false, both with their index fingers. Response keys were counterbalanced across participants. They were instructed to answer as quickly and accurately as possible.

Each trial started with a 200 ms blank screen (see Figure 1). A warning-fixation point (!) was then displayed at the center of the screen for 300 ms, followed by the equation. The equation remained on the screen until participants responded. During the intertrial interval, participants saw "XXXX" for 2,000 ms on the screen. Before the experiment, 16 training problems, similar to but different from the experimental problems, were presented. After the practice problems, participants saw 10 blocks of 64 problems each, with 5 min breaks between each block. Participants were individually tested in one session that lasted approximately 60–90 min.

Data Processing

Latencies larger than the mean of the participant + 2 *SD*s (4.3% and 3.5% in young and older adults, respectively) were excluded from analyses as well as all erroneously solved problems. In addition, the first trial of each block and every response time smaller than 300 ms were not included in the analyses. Data were analyzed to test age-related differences in (a) true/false and five/non-five problems, (b) strategy combination in false five problems, and (c) sequential modulations of rule-violation checking strategies. Unless otherwise noted, differences are significant at least to $p < .05$.

Results

Age-Related Differences in True–False and Five-Non-Five Problems

We conducted 2 age (young, older adults) × 2 problem type (five, non-five problems) × 2 correctness (true, false problems)

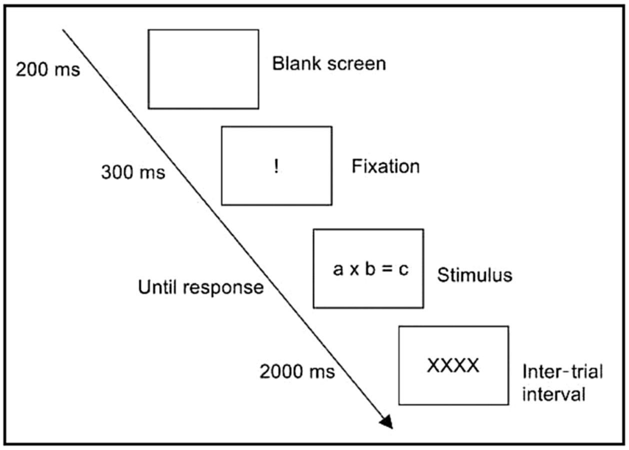

Figure 1. Sequence of events within a trial.

mixed-design analysis of variance (ANOVAs) on mean solution latencies and percentages of errors (see Table 2). Young adults were faster than older adults, $F(1,50) = 4.55$, mean squared error (MSe) = 539,289, $\eta p^2 = 0.08$. Overall, participants were faster for five problems (3,493 ms) compared with non-five problems (4,093 ms), $F(1,50) = 52.90$, MSe = 374,767, $\eta p^2 = 0.51$, and this difference was larger for young adults (933 ms) than for older adults (268 ms), $F(1,50) = 16.24$, MSe = 115,055, $\eta p^2 = 0.25$. Furthermore, participants were faster for false problems (3,361 ms) compared with true problems (4,226 ms), $F(1,50) = 121.39$, MSe = 777,270, $\eta p^2 = 0.71$. The problem type × correctness interaction was significant. It revealed a larger difference between five and non-five problems on true problems (915 ms) compared with false problems (285 ms), $F(1,50) = 68.46$, MSe = 103,388, $\eta p^2 = 0.58$, and this difference was larger for young than older adults, $F(1,50) = 4.21$, MSe = 6,357, $\eta p^2 = 0.08$.

Participants made fewer errors on five problems (5.3%) than on non-five problems (7.5%), $F(1,50) = 18.62$, MSe = 5, $\eta p^2 = 0.27$. The trial type × correctness interaction was significant, $F(1,50) = 49.60$, MSe = 14, $\eta p^2 = 0.50$, with a larger difference between five and non-five problems on true problems (5.8%) than on false problems (−1.5%). We arcsin corrected all error rates to normalize the data. Analyses yielded the same results as analyses on untransformed data.

Age-Related Differences on Rule-Violation Problems

The first goal of these analyses was to test age-related differences on no-rule, parity-rule, five-rule, and both-rule violation problems. Participants' performance on false five problems were analyzed with 2 age (young adults, older adults) × 4 rule violation on current problems (no-rule, parity-rule, five-rule, two-rule) mixed-design ANOVAs (Figure 2, Table 3). Young adults were faster than older adults, $F(1,50) = 11.48$, MSe = 1,045,372, $\eta p^2 = 0.19$. Moreover, there was a main effect of rule violation on current problems, $F(3,150) = 189.59$, MSe = 4,472,345, $\eta p^2 = 0.79$. Planned comparisons showed that participants were slower at rejecting no-rule violation (5,036 ms) problems than parity-rule violation problems (3,032 ms), $F(1,51) = 127.49$, MSe = 4,069,387, $\eta p^2 = 0.71$, five-rule violation problems (2,647 ms), $F(1,51) = 225.70$, MSe = 5,827,634, $\eta p^2 = 0.82$, and two-rule violation problems (2,548 ms), $F(1,51) = 243.18$, MSe = 7,026,744, $\eta p^2 = 0.83$. Moreover, participants took more time to reject parity-rule violation problems than five-rule violation problems, $F(1,51) = 26.96$, MSe = 157,432, $\eta p^2 = 0.35$ and two-rule violation problems, $F(1,51) = 60.72$, MSe = 401,358, $\eta p^2 = 0.54$. Most importantly, participants were faster to reject two-rule vwiolation problems than five-rule violation problems, $F(1,51) = 42.86$, MSe = 56,051, $\eta p^2 = 0.46$. The age × rule violation on current problems interaction, $F(3,150) = 5.35$, MSe = 42,040, $\eta p^2 = 0.10$, revealed larger benefits of two-rule violation problems for young compared with older adults. Indeed, young and older adults were 11% and 7%, respectively, faster on two-rule violation problems than on five-rule violation problems.

Errors rates showed a main effect of rule violation, $F(3,150) = 22.10$, MSe = 44, $\eta p^2 = 0.31$. Participants rejected no-rule violation problems less accurately than parity-rule violation problems, $F(1,51) = 22.16$, MSe = 148, $\eta p^2 = 0.30$, five-rule violation problems, $F(1,51) = 20.72$, MSe = 169, $\eta p^2 = 0.29$, and two-rule violation problems, $F(1,51) = 27.50$, MSe = 200, $\eta p^2 = 0.35$. Parity-rule violation problems were rejected equally accurately than five-rule violation problems, $F < 1.5$ while they were rejected less accurately than two-rule violation problems, $F(1,51) = 8.55$, MSe = 4, $\eta p^2 = 0.14$. Most importantly, two-rule violation problems were rejected more accurately than five-rule violation problems, $F(1,51) = 5.16$, MSe = 1, $\eta p^2 = 0.09$. There was no main effect or interaction involving the age factor (Fs < 1).

To analyze sequential modulations of rule-violation effects, participants' performance on false five problems were analyzed with 2 age (young adults, older adults) × 2 rule violation on previous problems (no-rule violation, rule

Table 2. Young and Older Adults' Mean Latencies (in ms) and Percentages of Errors for Five and Non-Five Problems

	Young adults			Older adults		
Problem type	True problems	False problems	Means	True problems	False problems	Means
Solution times (in ms)						
Non-five problems	4,509	3,290	3,900	4,857	3,717	4,287
Five problems	3,183	2,751	2,967	4,353	3,686	4,019
Means	3,846	3,021	3,434	4,605	3,701	4,153
Differences	1,326	539	933	504	31	268
Mean percentages of errors						
Non-five problems	9.7	4.2	6.9	10.8	5.2	8.0
Five problems	2.5	5.4	3.9	6.4	7.0	6.7
Means	6.1	4.8	5.4	8.6	6.1	7.3
Differences	7.2	−1.2	3.0	4.4	−1.8	1.3

violation) × 4 rule violation on current problems (no-rule, parity-rule, five-rule, two-rule) mixed-design ANOVAs. Young adults were faster than older adults, $F(1,50) = 11.55$, MSe = 2,300,743, $\eta p^2 = 0.19$. Furthermore, the age × rule violation on previous problems × rule violation on current problems was significant, $F(3,150) = 2.72$, MSe = 26,120, $\eta p^2 = 0.05$. Rule violation on previous problems × rule violation on current problems was significant in young adults ($F(3,75) = 2.94$, MSe = 49,237, $\eta p^2 = 0.11$) but not in older adults ($Fs < 1$). In young adults, contrasts revealed that two-rule violation problems were solved significantly faster than five-rule violation problems when previous problems violated arithmetic rules ($F(1,25) = 8.41$, MSe = 98,005, $\eta p^2 = 0.25$) but not following problems that respected these rules ($F < 2.5$). No other contrasts came out significant, suggesting that rule violation on the previous problems ($Fs < 3.5$) did not modulate performance on the current problems, except on the current two-rule violation problems. Moreover, two-rule violation effects (i.e., no-rule violation problems minus two-rule violation problems) were significantly larger following rule violation problems than when previous problems respected arithmetic rules (+2,715 ms vs. +1,990 ms, $F(1,25) = 4.43$, MSe = 273,097, $\eta p^2 = 0.15$). Neither parity-rule violation effects nor five-rule violation effects were modulated by previous rule violation ($Fs < 3.5$). Analyses of percentages of errors revealed no significant interactions ($Fs < 1.5$).

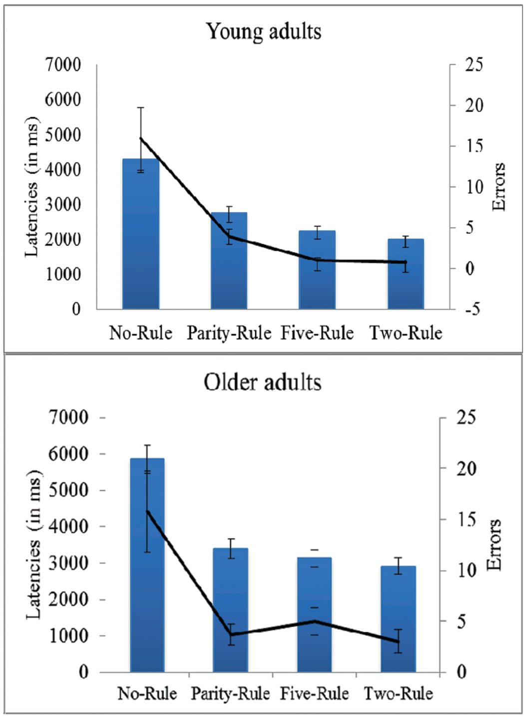

Figure 2. Mean solution times (bars) and percentages of errors (lines) in young and older adults as a function of false five problem types. Error bars represent standard error of the mean.

Discussion

The present study revealed several original findings on aging and strategic variations in the context of arithmetic problem verification. First, both groups had better

Table 3. Young and Older Adults' Mean Latencies (in ms) and Percentages of Errors for Current False Five Problems as a Function of Whether the Previous Five Problems Violated a Rule or No Rule

	Young adults		Older adults	
Target problems	Latencies (in ms)	% Errors	Latencies (in ms)	% Errors
Previous problem: no-rule violation				
No-rule violation	4,188	16.7	6,041	14.4
Parity-rule violation	2,728	3.8	3,534	5.0
Five-rule violation	2,321	2.1	3,185	4.7
Two-rule violation	2,198	0.0	3,321	5.0
Parity-rule violation effects	1,460**	12.9**	2,507**	9.4*
Five-rule violation effects	1,867**	14.6**	2,856**	9.7*
Two-rule violation effects	1,990**	16.7**	2,720**	9.4*
Previous problem: rule violation				
No-rule violation	4,469	18.5	5,447	10.8
Parity-rule violation	2,598	3.3	3,266	2.2
Five-rule violation	2,061	0.4	3,020	3.8
Two-rule violation	1,754	1.7	2,917	1.7
Parity-rule violation effects	1,871**	15.2**	2,181**	8.6*
Five-rule violation effects	2,408**	18.1**	2,427**	7.0^{ns}
Two-rule violation effects	2,715**	16.8**	2,530**	9.1*

Notes: Parity-rule violation effects = no-rule violation problems—parity-rule violation problems; five-rule violation effects = no-rule violation problems—five-rule violation problems; two-rule violation effects = no-rule violation problems—two-rule violation problems; ns, nonsignificant.
$^*p < .05$. $^{**}p < .01$.

performance on five problems than on non-five problems, and on false compared with true problems, replicating previous findings in arithmetic problem verification (e.g., Allen et al., 1992, 1997, 2005; Lemaire & Reder, 1999). Most originally, older participants used plausibility-checking strategies like five-rule and parity-rule violation checking strategies and were also able, although to a lesser extent than young adults, to combine them into a single, more efficient strategy. Moreover, strategy combination was modulated by which strategy was executed on the immediately preceding problem. We also found age-related differences in sequential modulations of strategy combination.

First, our results replicate Hinault and colleagues (2014)'s findings in young adults but also revealed that older adults used plausibility-checking strategies during arithmetic problem verification tasks. Older adults used, like young adults, different plausibility-checking strategies on different problem types: They used parity-rule, five-rule, and two-rule violation checking strategies. This led them to obtain better performance than when they used calculation strategies. Also, in both age groups, the five-rule violation checking strategy yielded faster latencies than the parity-rule violation checking strategy. These are interesting findings because previous research found that older adults did not use, or not as systematically as young adults, fast plausibility-checking strategy to reject large-split problems (e.g., $4 \times 8 = 39$) but rather mainly used exact calculation to solve all problems regardless of split size (Allen et al., 1992, 1997, 2005; Duverne & Lemaire, 2005; Duverne et al., 2008; El Yagoubi et al., 2005). Here, our results showed that older adults can use fast plausibility checking strategies in arithmetic problem verification tasks like they do in sentence verification tasks (Reder et al., 1986). Why they are more reluctant to use split-based plausibility-checking strategy than rule-violation checking strategy is an issue that deserves further investigations. Speculatively at this stage, it is possible that they trust their fast answer less on large-split problems than on rule-violation problems, leading them to use calculation strategy on large-split problems like they do on small-split problems.

Furthermore, we also observed strategy combination in older adults. Although the benefits associated with two-rule violation problems were smaller in older than in younger adults, both age groups were able to combine two-rule checking strategies into a single strategy, as seen in better performance while verifying two-rule violation problems than no-rule or one-rule violation problems. It is possible that smaller benefits associated with two-rule violation problems in older adults came from older adults' using strategy combination less systematically and/or less efficiently than young adults. Strategy combination occurred when participants verified two-rule violation problems by checking whether (a) an equation with five and an even operand had a product that ends with zero, and (b) an equation with five and an odd operand had a product that ends with five. Hinault and colleagues (2014) assumed that strategy combination in young adults occurred via accumulation of evidence of two rules being violated while encoding problems. It is highly likely that the same mechanism is responsible for strategy combination in older adults. Verbal reports as well as eye movement data could provide converging evidence for such interpretation in future works.

In contrast to what would happen if splits between correct and proposed answers were driving solution latencies, both age groups were faster on smaller-split problems (i.e., five-rule and two-rule violation problems) than on larger-splits problems (no-rule, parity-rule problems). Thus, despite well-known split effects in the arithmetic literature (Ashcraft & Battaglia, 1978; De Rammelaere et al., 2001; Zbrodoff & Logan, 1990), the present results suggest that arithmetic-rule violation checking prevails on the distance being the proposed and the correct answers.

We also found sequential modulations of rule-violation checking strategies in young adults. Young participants increased their speed when verifying two-rule violation problems after verifying rule-violation problems compared with after verifying no-rule violation problems. Such sequential modulations were not observed when current problems violated either parity rule or five rule only. Sequential modulations in strategy combination are consistent with previous findings regarding carry-over effects of strategy used on one problem on strategy used and/or executed on the next problem (Ardiale and Lemaire, 2012; Lemaire & Hinault, 2014; Lemaire & Lecacheur, 2010; Lemaire & Leclère, 2014; Luwel et al., 2009; Schillemans et al., 2011, 2012; Uittenhove & Lemaire, 2012, 2013). For example, Lemaire and Lecacheur (2010) found that participants were faster when asked to repeat the same strategy on two consecutive trials than when asked to use two different strategies while trying to find approximate products to two-digit multiplication problems. Here, rule-violation checking strategies were still in a high state of activation and more readily available after using a rule-violation checking strategy. This led participants to more quickly implement execution of the two-rule violation checking strategy. That such sequential modulations were not seen on problems violating only either the parity rule or the five rule suggests that it is not enough for a rule-violation checking strategy to be used on a given problem for it to be executed more quickly on the next problem.

Unfortunately, we did not have enough problems to determine whether speed up in verifying two-rule violation problems would be larger after verifying parity-rule, five-rule, or two-rule violation problems. This would have enabled us to compare benefits associated with two-rule violation checking strategy following strategy combination and following single-rule violation checking strategies. Finding, for example, that speed-up of verifying two-rule violation problems is comparable following one-rule violation problems (i.e., parity-rule and five-rule violation problems) and following two-rule violation problems would suggest that it is enough that one rule is violated on the preceding problem to trigger strategy combination on current problems. Alternatively, it may be necessary that both parity and five rules are violated on the preceding problems for the two-rule checking strategy to be executed more quickly on the current problems. Future studies undertaking such comparisons will help determine necessary and sufficient conditions for sequential modulations of strategy combination as well as further understanding the underlying mechanisms.

Older adults did not show sequential modulations of strategy combination. The differences in latencies between two-rule violation problems and one-rule violation problems were the same when current problems were preceded by no-rule violation problems and by rule-violation problems. This result is consistent with studies showing age-related changes in sequential modulations of strategy execution (Ardiale and Lemaire, 2012; Lemaire & Leclère, 2014), and may stem from residual activation of rule-violation checking strategies decreasing more quickly in older than in young adults following execution of rule-violation checking strategy. In this perspective, when they solve a new problem, older adults needed more time to reactivate the two-rule violation checking strategy. It is also possible that, with limited processing resources (see Park & Reuter-Lorenz, 2009, for a review), older adults tended to approach each problem individually. Indeed, participants could see two successive problems respecting (five, parity, or both) rules, two problems violating rules, one problem respecting rules followed by one problem violating rules, or one problem violating rules followed by one problem respecting rule. In this context, not trying to predict whether the next problem is going to respect or violate rule is using up fewer resources than trying to make such predictions.

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